The Role of Climate in Estuarine Variability

Studying an estuary as a component of the global climate system uncovers natural fluctuations that might otherwise be mistaken for anthropogenic trends

David Peterson, Daniel Cayan, Jeanne DiLeo, Marlene Noble and Michael Dettinger

One of the more awkward facts of California's hydrology is that 70 percent of the state's annual runoff of fresh water occurs north of Sacramento, whereas 80 percent of the state's water consumption takes place south of that city. To supply the south, increasing amounts of water have been diverted from the Sacramento and San Joaquin rivers, greatly reducing freshwater inflows to San Francisco Bay. These diversions have been of great interest to scientists concerned with the health of the bay, which is tied to fluctuations in salinity. They have looked closely at the flow from the Sacramento-San Joaquin Delta, the complex of islands and channels where the two rivers meet, which accounts for 90 percent of the freshwater inflow to the bay.

But sorting out the causes of the water-flow and salinity fluctuations in the delta and San Francisco Bay, and in many other estuary systems, is not a simple matter. A wide variety of climatic and human influences act on the estuary. Fluctuations in climate would cause freshwater inflow to the bay to vary dramatically from year to year, even without large diversions upstream. And the diversions themselves vary from year to year.

It is not surprising, given all these influences, that the salinity of the bay is highly variable and has been rising. Between winter and summer most years, salinity varies as much as 10 parts per thousand—an enormous fluctuation when one considers that the salinity of coastal ocean water is normally just over 33 parts per thousand. And bay salinity varies by a similar amount from year to year. Over the longer term—a matter of particular concern—spring salinities have been slowly rising over the past few decades, increasing by 3 parts per thousand since 1941.

The diversion of fresh water is a large part of the story. Largely because of diversions for agricultural uses, it is estimated that the delta flow is less than 50 percent of its volume in 1850 (although estimates are uncertain because flows were not measured before development took place). Diversion is clearly responsible for much of the salinity increase, but does it account for all of it? To what extent, for instance, might the salinity trend reflect natural fluctuations, such as winter warming or a shift to weather patterns that favor the upwelling of saline water off the coast?

It is one thing to ask these questions and quite another to answer them. Distinguishing short- and long-term anthropogenic trends from the fluctuations of a natural system can be very difficult. To make this distinction in estuarine dynamics we must take a much broader view of estuarine systems than scientists have usually taken.

An example of the approach taken in the past is a sprawling scale model of San Francisco Bay located in a warehouse in Sausalito that has sometimes

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Figure 1. A new approach to estuarine dynamics considers the estuary in the context of the land, sea and atmosphere. Estuaries have traditionally been treated as isolated hy-

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draulic bodies. Inputs from upstream watersheds and the coastal ocean were taken as external parameters, and the watersheds and ocean were regarded as independent of one another. In reality, watershed, estuarine and oceanic processes are coupled by the atmosphere that so magnificently dominates this photograph of San Francisco. Through terrestrial and oceanic linkages, the large-scale atmospheric circulation patterns influence estuarine variables on scales of seasons, years and decades.

been used to study the effects of water exports on salinity distributions. When a salinity study is run on the model, the freshwater supply is programmed to vary as it has been observed to vary during field surveys, and the salinity distribution in the scaled-down estuary is then measured with and without proposed exports. Given the way the problem is framed, any change in the salinity distribution that a study uncovers is necessarily caused by freshwater diversions rather than by natural fluctuations.

Like the bay-model studies, most scientific studies of estuarine dynamics have taken the known variability of river flow as a given. At the U.S. Geological Survey, however, we are also attempting to discover *why* river flow varies. To do so we are studying the estuary as a component of the global climate system rather than in isolation. In effect we have taken the roof off the Sausalito warehouse and knocked down its walls, allowing it to experience the same storms as are supplying its inflow from the high Sierras. By this means, we have been able to demonstrate that much of the year-to-year variability and part of the long-term salinity trend do indeed result from natural fluctuations in the large-scale

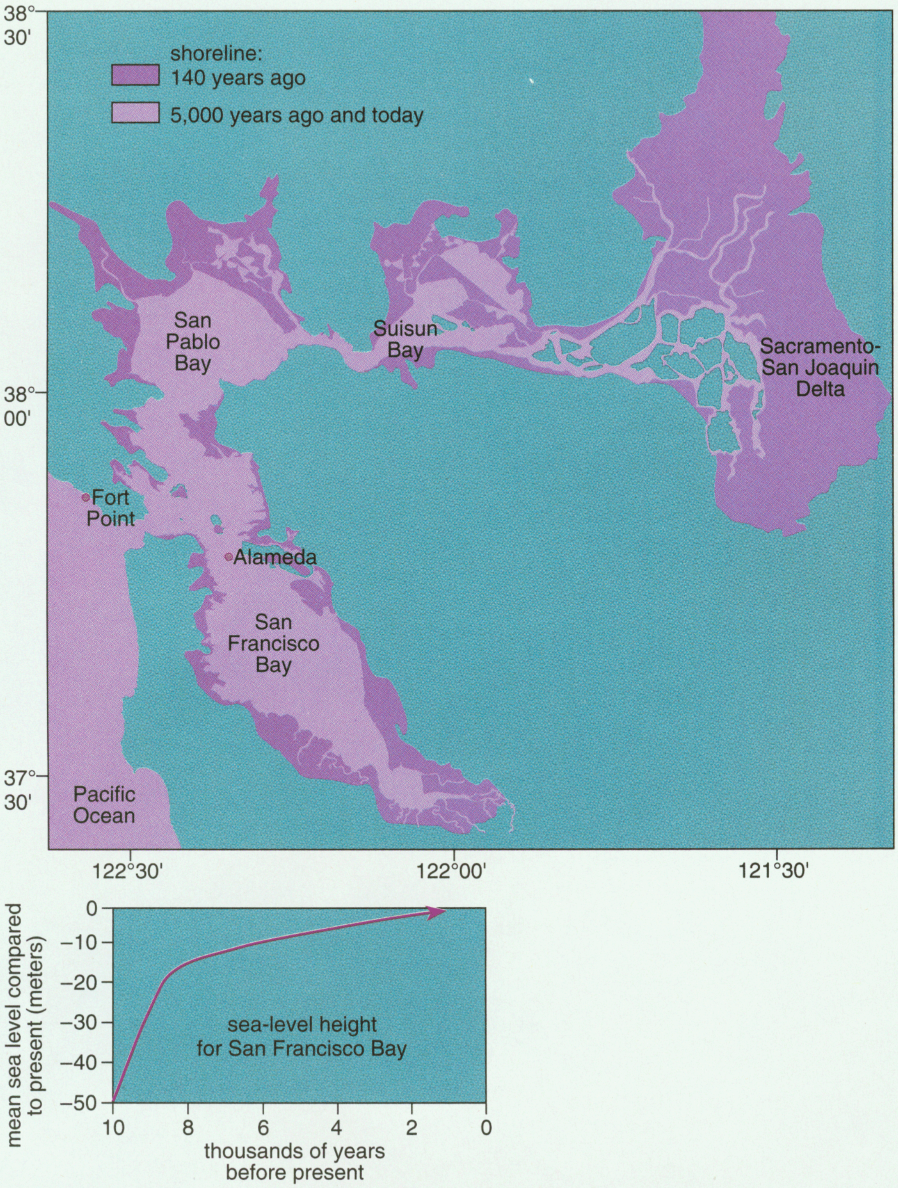


Figure 2. Human activity has had dramatic effects on San Francisco Bay, as can be seen by comparing shorelines over the past 5,000 years. Sea level *(graph)* has been increasing at a nearly constant rate of 2.5 millimeters per year over the time period. As sea level rose, the bay grew, covering the area in violet 5,000 years ago and the area in purple 140 years ago. More recently, however, human activities, such as diking, draining, land reclamation and hydraulic mining, began to push the shoreline back again. Today the shoreline is roughly where it was 5, 000 years ago, even though the sea level has continued to rise.

atmospheric circulation patterns that govern the weather over California.

We suspect that this broader approach to modeling estuarine dynamics will become more common as scientists are increasingly called on to distinguish between the effects of climate and of human activities on estuarine variables. In Chesapeake Bay, for example, one focus of concern is an increase in the volume of anoxic, or oxygen-depleted, water. People have doubtless contributed to the oxygen depletion by allowing sewage and fertilizers, which fuel the growth of oxygen-consuming organisms, to flow into the bay. The spring runoff also contributes to anoxia, however, by stratifying bay water and thus preventing oxygen from being exchanged between the atmosphere and the depths of the bay. It has been suggested that spring runoff may have increased over the past century because of deforestation in the bay's watershed. But deforestation cannot explain year-to-year fluctuations in the volume of anoxic water, which appear to be caused instead by climate fluctuations. To untangle the contributions of these two forcing factors, scientists must include within their model of the estuarine system the whole river basin and the prevailing atmospheric circulation patterns, and not just the estuary itself.

Estuarine Salinities

Perhaps the best way to illustrate the nature of estuarine variability is to examine salinity patterns in San Francisco Bay, which fluctuate over several different time scales.

A glance at the 65-year record of monthly salinity anomalies in Figure 3 shows that in addition to monthly variability, there are slower seasonal fluctuations in salinity. At the mouth of the bay, the seasonal increase or decrease can be 20 percent of the average annual salinity. Even larger salinity changes occur farther inland, because the salt field, or seawater front, shifts within the bay in response to freshwater inflows. Over years to decades, salinity also responds to climate changes, presumably because climate governs runoff into the estuary.

The salinity distribution in the bay is determined by the balance between the freshwater inflows from the delta and the coastal-ocean salinity. Of these two variables, delta flow is by far the more important. Even at the mouth of the estuary, delta flow explains some 86 percent of the observed variability in salinity.

The volume of delta flow has the biggest effect on estuarine salinity, although its timing exerts a smaller effect. The volume of delta flow, in turn, is largely determined by winter precipitation, because 55 percent of the annual precipitation typically falls in the months of January, February and March. If winter precipitation is high, increased runoff continues well into the summer and tends to dilute salinity in the estuary throughout the summer. Conversely, if winter precipitation is low, warm-season runoff tends to be low, and estuarine salinity in summer tends to be high.

This winter climate effect is modulated by a springtime one. The temperature and precipitation in spring together modify salinities in the estuary by affecting the timing and, to some extent, the volume of spring inflows. If spring is rainy, skies are cloudy and temperatures remain cool. Under these circumstances, the snow pack in the Sierra Nevada persists longer than usual, the peak river flow into the bay

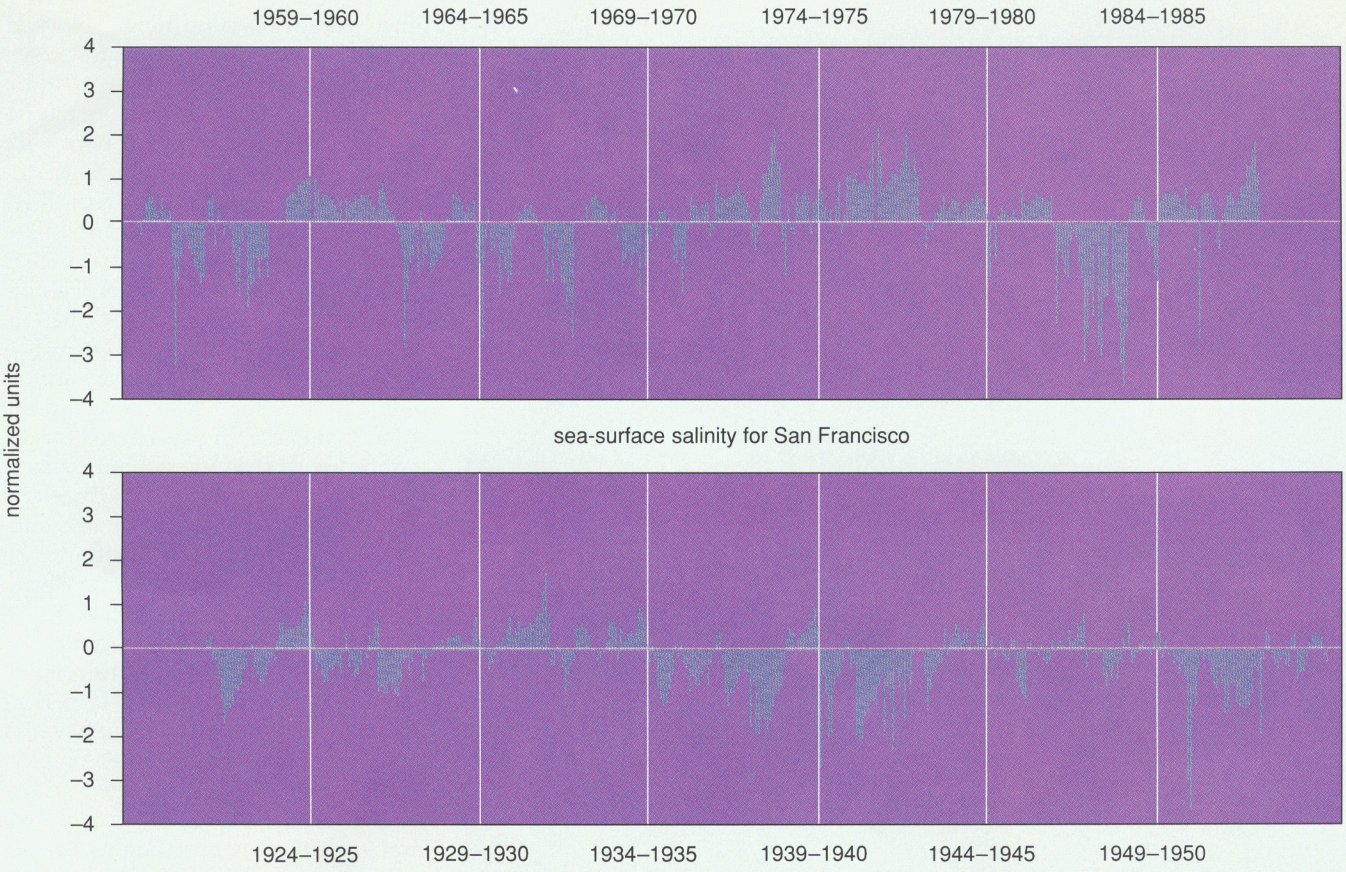


Figure 3. Understanding of estuarine dynamics in San Francisco Bay is taxed by the salinity fluctuations, which occur at several different time scales. Shown here are the salinity anomalies at Fort Point, near the mouth of the bay. The long-term salinity trend has been removed from the data, leaving only the monthly fluctuation in salinity.

is delayed or prolonged into late spring or early summer, and the total runoff tends to be high. In contrast, if spring is dry, skies are clear and daytime temperatures are warm. The spring runoff doesn't last as long, and the total runoff tends to be low. For both reasons, dry springs result in the highest summer salinities, and wet springs result in the lowest summer salinities.

Springtime conditions in the coastal ocean also modulate the estuarine response to delta flow. The coastal effect is difficult to untangle from the others because it is quite small and because it responds to the same atmospheric forcing patterns as the delta flow. Typically, in response to southward winds, there is an upwelling of deeper, saltier seawater along the West Coast from March until fall. This period of intensifying upwelling coincides with the period of decreasing delta flow. When the saltier water is transported or mixed into the Bay, it tends to increase salinities there. Salinity data show, however, that high delta flow in the spring frequently masks the effects of coastal upwelling on estuarine salinity, even near the mouth of the estuary.

The biological effects of these geophysical events are very sensitive to the event's timing. Recently there has been a decline in the fraction of the delta flow arriving in the spring, and fisheries managers are concerned that lower flows and higher water temperatures may disturb spawning and larval transport or threaten the survival of fingerlings. Lower spring flows also alter the summer salt field, or salinity distribution, although comparatively little is known about the effect of the salt field on estuarine habitats. There is enough concern, however, that fisheries managers have proposed that specific positions for lines of constant salinity be adopted as a new water-chemistry standard against which the management of the bay is judged.

Atmospheric Teleconnections

Understanding the net effect of the many interacting physical processes that govern the state of an ecosystem is never easy, but it is particularly difficult in the case of an estuary. Lying on the boundary between the land and the sea, an estuary is subject to both terrestrial and oceanic physical processes and to varied and interesting climatic effects. If each contributing process and its interactions with other processes had to be individually considered, the problem would be overwhelmingly complex. This is why it is useful to recognize that the large-scale patterns in atmospheric circulation couple with and organize geophysical processes. These overarching patterns allow us to understand estuarine dynamics without oversimplifying them.

The San Francisco area has a Mediterranean climate characterized by warm dry summers and cool, wet winters. The climate is governed by a big high-pressure cell that blossoms over the North Pacific in the summer. This cell deflects storms to the north, preventing measurable precipitation over California. During winter the cell migrates south and becomes less intense. As the Pacific High weakens, the Aleutian-Alaskan Low strengthens. Temperature and pressure gradients between the tropics and the pole become steeper, and many more weather disturbances stream across the Pacific.

Influences on San Francisco Bay salinity

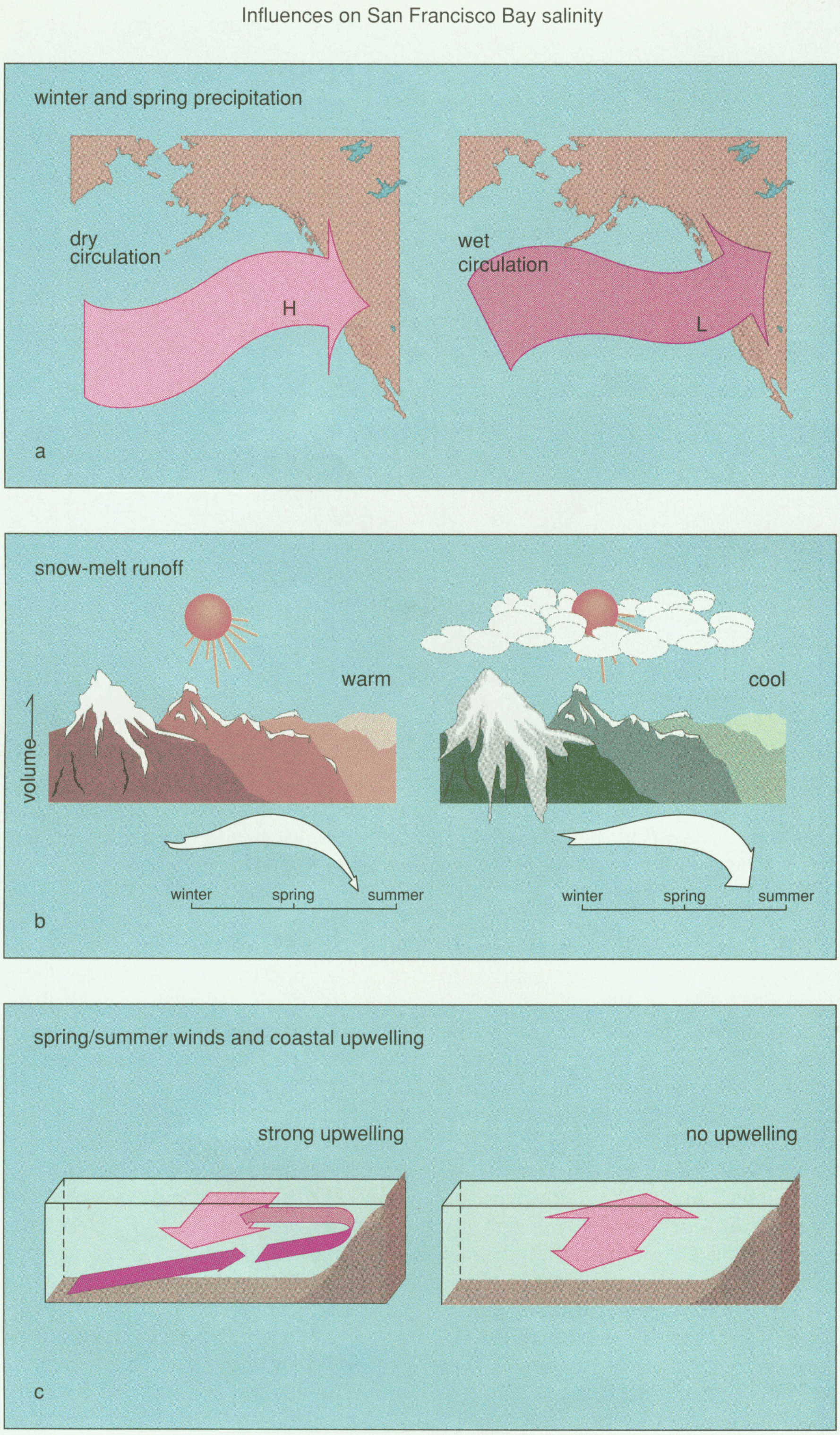


Figure 4. Large-scale weather patterns affect bay salinities by influencing winter precipitation, spring runoff and coastal upwelling. Winter and spring precipitation *(a)* have by far the strongest influence on bay salinities. A high-pressure system results in low precipitation *(left)*, whereas a low-pressure system increases precipitation. Springtime weather *(b)* modulates the winter effect primarily by determining the timing of runoff. A warm, sunny spring produces earlier snowmelt, which depletes summer freshwater flow *(left)*; a cool, cloudy spring delays snowmelt, prolonging high freshwater flow *(right)*. A final variable *(c)* is the direction of offshore winds in spring. Equatorward winds produce coastal upwelling, which increases salinity. Although they do not always occur together, these three influences—a dry winter, a warm spring and winds favorable to upwelling—all act to increase bay salinities.

Since California is no longer blocked by the Pacific High, the winter storm track passes over it.

At least, this is the pattern in a typical year. We are concerned here with variations in delta flow, which are driven by variations from this typical sequence of atmospheric events. One prominent large-scale pattern that causes unusual weather over California is an El Niño/Southern Oscillation, or ENSO, event. An ENSO event is a large irregularity in the coupled atmospheric and oceanic systems along the equatorial Pacific. It was named for the independently discovered but dynamically linked reversal of the pressure distribution over the tropical and subtropical Pacific, called the Southern Oscillation, and the Christmastime warming of the ocean off the coast of South America, called an El Niño event.

Although ENSO events are concentrated in the tropical Pacific Basin, they generate very slowly varying waves that propagate away from the region through both the atmosphere and the ocean. These waves produce very large-scale climatic correlations, or teleconnections, and through these ENSOs have far-flung global effects.

In the tropical and subtropical Pacific, seasonal climate variability is remarkably tuned to the Southern Oscillation Index, the standard measure of ENSO intensity. But in extratropical regions, ENSO influences are more tenuous, and regional climatic influences and variations modulate the ENSO signal. In general the northwestern United States and southwestern Canada tend to be dry during the winter of a mature phase of an ENSO event. The southwestern United States tends to be wet during the same phase, as does the Gulf Coast and south Florida.

California, on the other hand, is located at the geographic boundary between these two responses and can experience either dry or wet weather. It turns out that precipitation in northern and central California during an ENSO event is better predicted by the location of the Aleutian-Alaskan Low than by the value of the Southern Oscillation Index.

The low is usually more intense than normal during an ENSO event, but its location varies. When the Aleutian-Alaskan Low forms farther east than usual, that is, nearer to the West Coast, as it did during the winter of 1983, storms penetrate into central California and the winter is wet. (By meteorological convention, the winter of 1983 includes December 1982 and January and February of 1983.) When the low forms farther west, that is, nearer the International Date Line, as it did in the winter of 1977, high-pressure anomalies tend to be found off the California coast. These anomalies deflect storms northward, keeping California dry.

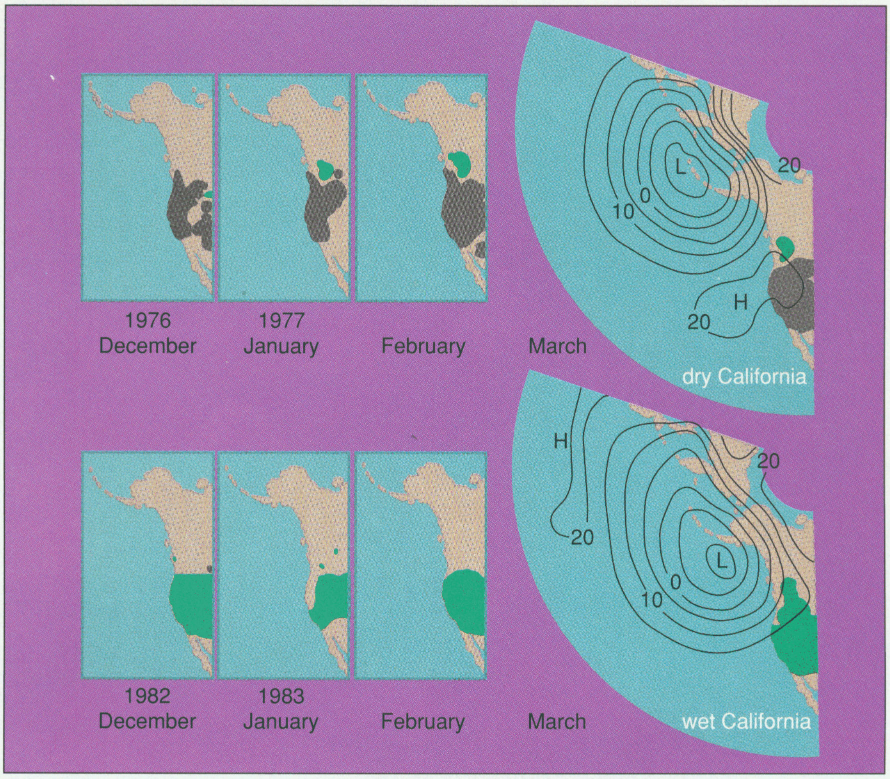
ENSO events may appear on either side of the precipitation balance sheet, but they are usually associated with extreme weather conditions. For example, the ENSO winters of 1941, 1958, 1983 and 1993 were very wet because central North Pacific storms took a southern path into California. On the other hand, the ENSO winters of 1977, 1987 and 1992 were extremely dry over much of the state because high pressure developed over the West Coast and North Pacific storms were diverted to the north.

Although ENSO events alone do not predict California weather, two of the authors (Cayan and Peterson) have defined a regional index that captures the effect of an ENSO event on Californian weather. This index, called the California Pressure Anomaly, or CPA, is calculated from sea-level pressure anomalies in a small region off the coast of California where the pressure anomalies have historically exhibited the strongest correlation with river-flow variability. The CPA region, which measures about 15 degrees longitude by 10 degrees latitude, is centered at 40 degrees north latitude and 135 degrees west longitude.

Years with high CPA winters are characterized by anomalously high pressure that deflects moisture-bearing storms to the north, resulting in reduced precipitation, lower delta flow and higher bay salinities. Years with low CPA winters are stormier, resulting in increased snowpack, greater delta flow and relatively low salinities. Unfortunately, meteorologists are not yet able to predict the CPA.

Oceanic Teleconnections

An ENSO event can have oceanic as well as atmospheric teleconnections with conditions in California. The ocean transmits a signal, possibly by means of a coastally trapped wave, that increases sea-level heights and sea-surface temperatures along the West Coast. During the ENSO event of 1983, for example, sea levels in the San Francisco Bay area



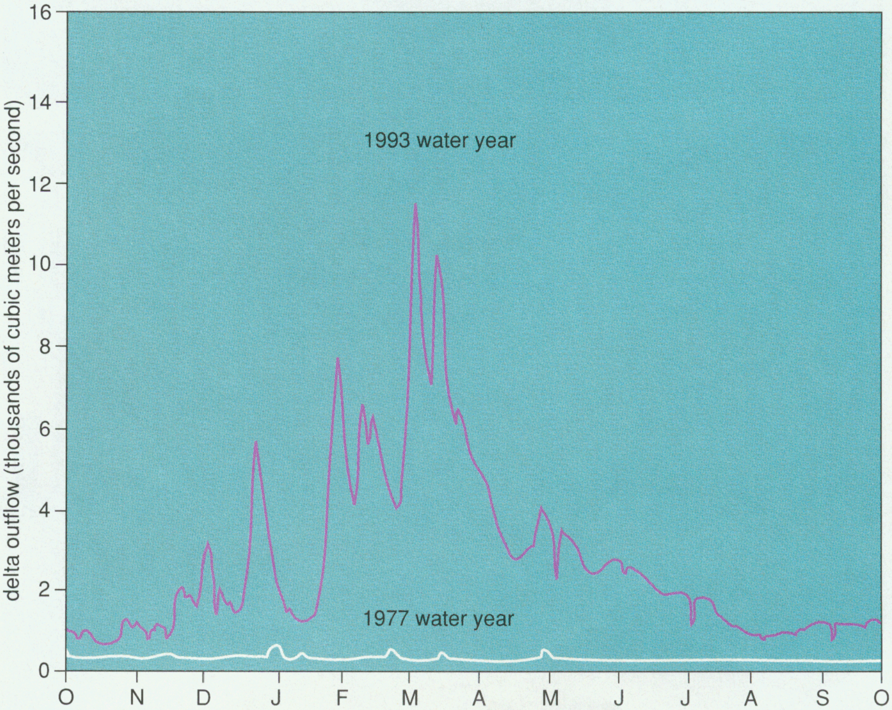


Figure 5. El Niño/Southern Oscillation (ENSO) events do not have a unique Californian signature. Precipitation patterns are correlated instead with the east-west location of the Aleutian-Alaskan Low. If the low is farther west than normal, as it was in the winter off 1977, a high-pressure cell forms over California, protecting it from winter storms *(top)*. If the low is farther east than normal, as it was in 1983, storms penetrate into central California and the winter is wet *(middle)*. Brown corresponds to monthly river flow in the lowest quartile and green to a monthly river flow in the highest quartile. Isobar units are millibars. Actual flows for the two years are shown in the graph at bottom.

Figure 6. Two ENSO events have been particularly destructive in this century. The February 1926 event produced storm waves that broke second-story windows of the Capitola Hotel (*top*). The 1983 event was also accompanied by larger sea-level height anomalies, which made it even more destructive. Shown at bottom are waves topping the breakwater at Capitola and battering Venetian Courts. (Top photograph courtesy of the Sandy Lydon collection; bottom photograph by Sandy Lydon.)

were about 10 centimeters higher than predicted and sea-surface temperatures were between 1 and 3 degrees Celsius warmer than normal.

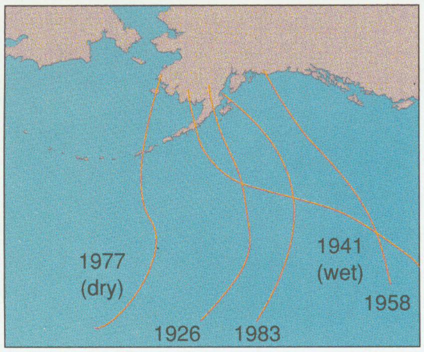
Again the effect of this teleconnection on California is difficult to predict. Sea-level heights near the mouth of San Francisco Bay are forced by a combination of global, regional and local mechanisms. An ENSO event can cause changes in sea level, but so can winds along the central California coast. During some years, the two phenomena reinforce one another, whereas in other years they oppose one another. An additional complication is that the oceanic signal of an ENSO event can be either enhanced or damped by the atmospheric signal.

The ENSO event in 1926 illustrates this modulation. For the most part ENSO events appear as large humps in the filtered record of sea-level heights at the mouth of San Francisco Bay (see Figure 7). The strong ENSO event of 1926 did not produce a sea-level rise like those that occurred during 1941, 1958 and 1983, however.

The large-scale sea-level pressure patterns were similar during the four ENSO events, which suggests that the wind patterns were also similar. A small deviation from the pattern appeared in January 1926, however. A regional high developed north of California in January, faded in February and reappeared in March.

This comparatively small perturbation in the atmospheric patterns had a major effect on California weather. For most of the winter, central Pacific storms tracked to the north rather than to the east, avoiding the regional high-pressure cell and California. Thus the regional high effectively blocked the large-scale storminess and the sea-level-height anomalies associated with it. When the blocking ridge temporarily disappeared in February, there was a spate of storms over the West Coast and central California and a minor rise in sea-level heights off the coast. By contrast, in 1941, 1958 and 1983 there were storms throughout the winter and the coastal sea-level-height anomalies were much larger and more persistent.

Even though conditions during February 1926 set no records, they were fairly impressive. At Seacliff, about 40 miles south of San Francisco, a developer named W. I. Morgan had been building a seawall designed to withstand "the greatest waves imaginable."



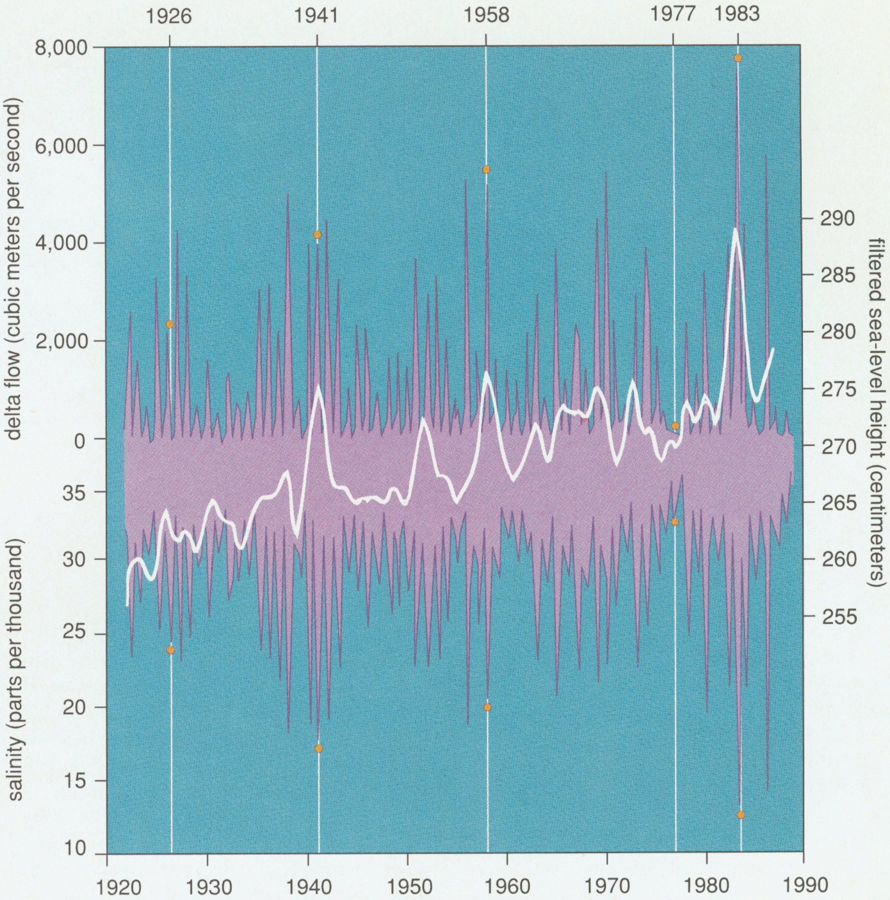


Figure 7. History of ENSO events demonstrates how the location of the atmospheric pressure anomaly *(above)* governs delta flow and sea-level height *(right)*. In an ENSO year when the pressure anomaly is close to the West Coast, such as 1941 or 1983, coastal winds amplify the oceanic teleconnection and push sea levels higher than normal. Because the winter storm track passes over California, runoff is high and salinity is low. When the anomaly is far offshore, as it was in 1977, sea levels are lower. Because the winter storm track deviates to the north of California, runoff is low and salinity is high.

In February 1926, however, the ocean destroyed this and other seawalls along the coast. Huge combers even broke second-story windows of the ocean-front Capitola Hotel.

During the ENSO event of 1983, unlike that in 1926, everything conspired to increase sea levels. A huge ENSO event in the Pacific propagated up the coast in the form of a wave, increasing sea levels. The sea-level increase happened to coincide with high astronomical tides and heavy river flows. For all three reasons the coast was unusually vulnerable to high storm waves. As a result of the 1983 storms, damage to public beach and pier structures alone was estimated at 50 million dollars. Damage to private property was estimated in the hundreds of millions of dollars.

Because higher sea levels at the mouth of the bay push salt water farther into the estuary, the sea-level signal of an ENSO event is an example of atmospheric coupling through oceanic processes to estuarine variables. This coupling, however, probably has minimal influence on estuarine salinities. The regional atmospheric response to an ENSO event (that is, the atmospheric signal) is probably more important. A high winter CPA is associated with stronger northerly (equatorward) winds that tend to increase the coastal upwelling of saline water. A low winter CPA is associated with southerly winds that do not favor upwelling and may even encourage downwelling. Since high-CPA winters tend to be dry and low-CPA winters to be wet, the CPA-governed changes in precipitation and coastal salinities act in concert on estuarine salinities.

Long-Term Trends in Salinity

ENSO events are relatively short-term fluctuations in atmospheric circulation patterns, although they provide useful tests of our understanding of atmospheric forcing of bay variables. Are

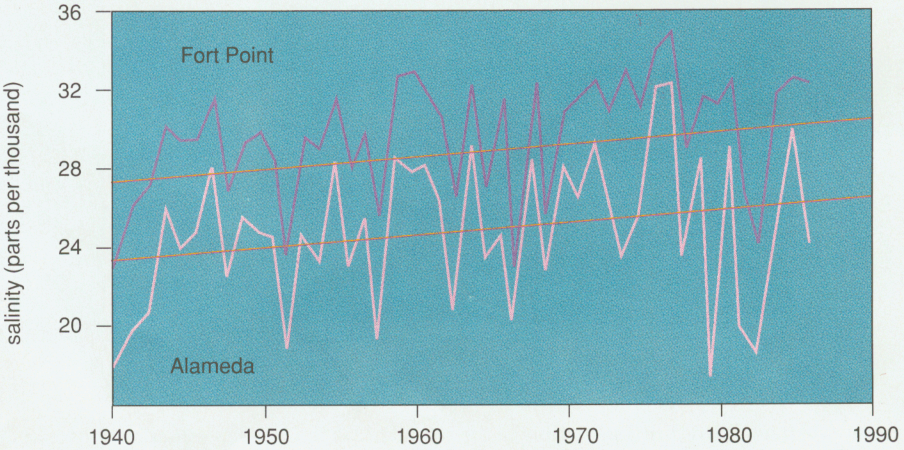


Figure 8. Spring salinities in San Francisco Bay have increased gradually over the past several decades. Shown here are the trends in the May salinities at Fort Point, which is near the mouth of bay, and at Alameda, which lies across the bay from San Francisco.

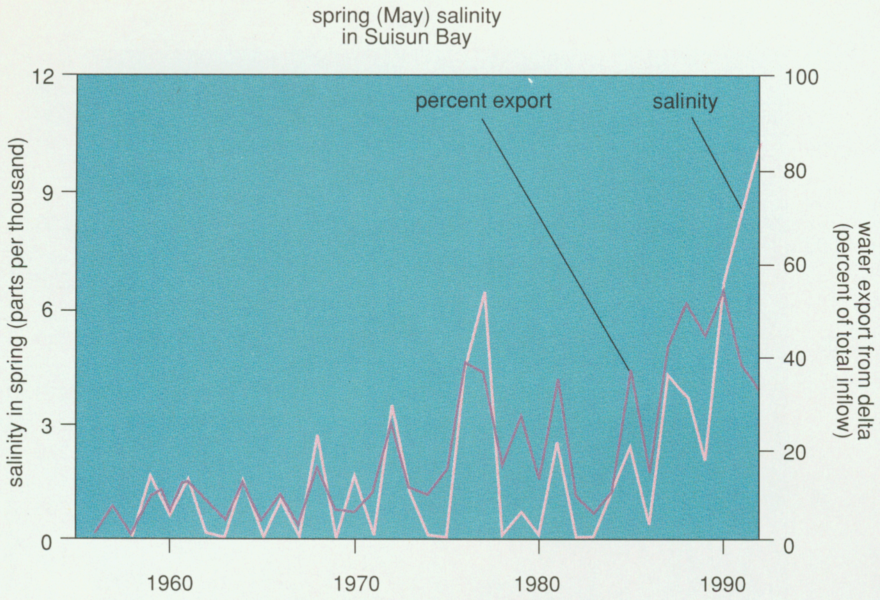


Figure 9. Spring salinities in Suisun Bay are correlated with water diversions both from year to year and over the long term. A greater percentage of the total flow is exported in dry years, and a smaller percentage of the total flow is exported in wet years. At the same time, the diversion of water in the spring has been increasing, just as have spring salinity values. (The annual rather than the spring export is shown here, but more water is exported in spring than in other seasons of the year.) As these correlations suggest, water exports account for most of the salinity trend, although there is also a small climate-related contribution.

there long-term trends in North Pacific atmospheric circulation patterns? If so, how are they affecting the bay?

The 1920s and 1930s were dry in California, and river-flow anomalies were persistently negative. Estimates of total annual delta flow, which were first recorded in the early 1920s, indicate that the total flow today is almost the same as the flow during this dry era. Since then, the average flow has not increased because increased precipitation has been offset by a nearly equivalent increase in human consumption. Although the total annual flow has remained relatively constant, the distribution of flow over the annual cycle has changed. Over time, delta flow has increased in early winter and decreased in spring.

This long-term decline in spring flow into the bay explains most of the long-term rise in spring salinities and, in turn, is mostly the result of increasing agricultural consumption. Indeed, we estimate very roughly that water exports from the rivers and delta account for at least 80 percent of the salinity trend.

To complicate matters, however, the decline also includes climate-driven contributions. The main climate effect is a trend toward warmer winters, which has led to less snowpack accumulation and therefore to less snowmelt discharge in spring. The decline in spring runoff, which was discovered by Maurice Roos of the California Department of Water Resources, was, in fact, what tipped meteorologists off to the winter warming. It has been suggested by some that the winter warming might be a local manifestation of greenhouse warming. The local warming can as easily be explained, however, by the fact that over the past several decades the winter wind field over the North Pacific has been displaced progressively southward. On balance, we think the winter warming is more likely to prove to be a natural fluctuation of the atmospheric circulation pattern than a unidirectional trend in the global climate.

A second climate effect is a small decrease in spring precipitation. This effect may be traceable to a recent tendency for high-pressure zones south and west of San Francisco to strengthen and migrate northward in the spring. The high-pressure zones tend to divert storms approaching California from the west, so that the spring remains dry.

The same atmospheric pattern has also tended to increase spring sea-surface salinities at the mouth of the bay. The stronger off shore high-pressure

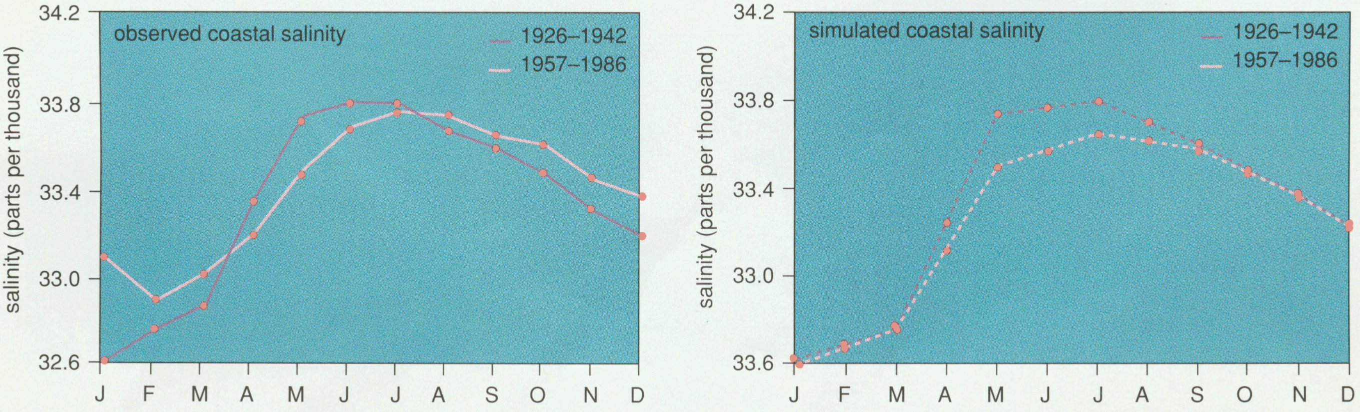


Figure 10. Intensified spring upwelling in the coastal ocean is a trend in estuarine dynamics that may reflect the influence of climate. Andrew Bakun of the National Oceanic and Atmospheric Administration, who discovered this intensification, argued that it was an indirect effect of greenhouse warming. The authors think that the stronger upwelling along the West Coast might instead reflect a low-frequency variation in the regional atmospheric circulation. Using the California Pressure Anomaly as an index of the strength of winds that favor upwelling, they were able to simulate the fluctuation in coastal salinities at the Farallonƒ Islands, about 45 kilometers offshore from the bay, from 1926 to 1942 and from 1957 to 1986.

zones have strengthened equatorward wind components in spring. These winds lower the coastal sea level and encourage coastal upwelling, which increases coastal salinities. Andrew Bakun of the National Oceanic and Atmospheric Administration, who first discovered the spring increase in coastal upwelling, identified a similar trend at coastal locations around the world and therefore argued that stronger upwelling was an indirect effect of greenhouse warming. Coastal upwelling is known for its short-period intermittence, however, and it has also been shown to vary over periods of thousands years. For this reason we again find no reason to assume that the recent change in the upwelling was caused by human activity rather than by the natural wandering of the climate system.

Both of the springtime trends—less precipitation and more coastal upwelling—are understandable in terms of an observed long-term rise in the spring CPA. Mathematical analysis indicates that the CPA rise has been sufficient to account for the spring decline in the fraction of delta flow not explained by water diversions, for the slight increase in spring coastal salinities, and for the combined effect of drier springs and a saltier ocean on salinities within the bay.

What are the implications of these findings for the future of the bay? Assuming that we are witnessing climate fluctuations rather than climate trends, the climate-induced portion of the spring salinity trend might reverse direction at any time, acting to oppose rather than to exacerbate the impacts of water exports. This does not mean that we can withdraw more water from the delta with impunity, because the natural fluctuations could also change so as to increase salinity trends even more. Although these findings serve to remind us that not all estuarine variability is anthropogenic, they show further that, just as human beings may not be able to claim all the blame for salinity increases, neither can we expect to claim complete control over future variations.

The upstream watersheds, the offshore ocean and, as a unifying force, the atmosphere overhead all affect estuarine variables. On the time scales considered in this article, estuarine variability is linked to variations in atmospheric circulation through precipitation and runoff from the upland river basin and through wind-driven salinity variations in the coastal ocean. In the past several decades the climate has tended to increase salinities in the bay, but in our judgment this is just a passing effect of an endlessly varying North Pacific climate system. To paraphrase Heraclitus, not all is flux, but some certainly is.

Acknowledgments

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According to a two-year, double-blind, placebo-controlled clinical trial, I'm the bluebird of happiness.